REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98-

0168

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	31 Jan 98	Final (01 Nov 93 – 30 Jun 97)

4. TITLE AND SUBTITLE Broadband Signal Enhancement of Seismic Array Data: Application to Long-period Surface Waves and High-frequency Wavefields	5. FUNDING NUMBERS F49620-94-1-0039
6. AUTHORS Gary L. Pavlis	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Indiana University (Department of Geological Sciences) Bloomington, IN 47405	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 110 Duncan Avenue, Room B-115 Bolling Air Force Base, DC 20332-8080	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objectives of this program of broadband signal enhancement of seismic array data were the a) Development of new techniques for enhancement of low signal-to-noise surface wave signals recorded by broadband seismic arrays. The tasks were: Assembly of test data sets; Estimation of dispersion curves for reference events; Algorithm development. b) Research on fundamental properties of high-frequency wavefields. The tasks were: Analysis of array data using scientific visualization tools; Analysis of signal coherence versus receiver separation and frequency for different array data; Analysis of frequency dependent polarization for different array data.

19980219 116

14. SUBJECT TERMS	15. NUMBER OF PAGES
seismic array data, wavefields	
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

FINAL TECHNICAL REPORT
AFOSR GRANT F49620-94-0039

Broadband Signal Enhancement of Seismic Array Data:
Application to Long-period Surface Waves and High-frequency wavefields

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Report period: November 1, 1993 - June 30, 1997

Objectives

Task 1. Development of new technique for enhancement of low signal-to-noise surface wave signals recorded by broadband seismic arrays.

Subtask 1.1. Assembly of test data sets.

Subtask 1.2. Estimation of dispersion curves for reference events.

Subtask 1.3. Algorithm development

Task 2. Research on fundamental properties of high-frequency wavefields.

Subtask 2.1. Analysis of array data using scientific visualization tools.

Subtask 2.2. Analysis of signal coherence versus receiver separation and frequency for different array data

Subtask 2.3. Analysis of frequency dependent polarization for different array data

Accomplishments/New Findings

Improved understanding of surface wave propagation. A good deal of our efforts on Task 1 were directed at an improved understanding of how surface wave propagate in the real world. This is important to the Air Force's mission for global monitoring of underground nuclear explosions because the standard method of discrimination of nuclear explosion from earthquakes is the M_s-m_b technique. This compares amplitudes of surface wave and body wave signals. Outstanding practical issues are the transportability of this discriminate to regions outside regions of interest for nonproliferation and how the lower limit of this technique could be pushed with modern broadband seismic arrays.

New data from the Kyrgyzstan Network (KNET) operated under the IRIS Joint Seismic Program provided a valuable resource to study this issue. Two papers on this subject summarize the results of this work. The first is in press, and a xerox copy of the camera ready copy is enclosed with this report:

Mahdi, H. and G. L. Pavlis (in press). Velocity variations in the crust and upper mantle beneath the Tien Shan inferred from Rayleigh wave dispersion: Implications for tectonic and dynamic processes, *J. Geophys. Res.*.

It will probably appear in the February or March issue in 1998. Reprints of the second article are attached:

Pavlis, G.L., and H. Mahdi (1996). Surface wave propagation in central Asia: Observations

of scattering and multipathing with the Kyrgystan broadband array, *J. Geophys. Res.*, **101**, 8427-8455.

In addition to these two published works, two of our reports submitted for the yearly seismic research symposium also addressed this task. Copies of these are also attached. The citations are as follows:

Pavlis, G. L. and H. Mahdi (1995). The spatial stability of Rayleigh wave amplitudes and path dependent propagation characteristics of central Asia, *Proc. of 17th annual Seismic Research Symposium, Report PL-TR-95-2108,* pp. 291-298.

Pavlis, G.L., H. Mahdi, and F.L. Vernon (1994). Surface-wave propagation in Central Asia: Observations of scattering and multipathing with the Krygyz broadband array, in *Proceedings of 16th Annual Seismic Research Symposium*, Air Force Office of Scientific Research, Bolling AFB, DC., pp. 291-297.

The first is still under preparation for publication. It has not yet been submitted, but we hope to do so in the near future. The second is preliminary work that led to the two JGR papers.

Task 2. Our work in this area focused on three areas: precise quantification of seismic amplitude variations across various three-component seismic arrays, scientific visualization, and quantification of wavefield properties using the newly developed multiwavelet transform. I will describe results from each set of investigations separately and then summarize the primary understanding revealed by this work.

Amplitude studies. We worked extensively on spectral measurements made on signals recorded in three different seismic array experiments: (a) a high-frequency array experiment conducted at Pinyon Flat in 1990; (b) a broadband array experiment conducted at the same site in 1991; and (c) a new array installed in Turkmensitan in the summer of 1993. A common feature of all sites was dramatic variability of observed spectra at frequencies over a few Hz. We found clear evidence for a strong frequency dependence of spectral variability. A low frequencies, we found spectral estimates were identical at all stations, but scatter in results increased dramatically with increasing frequency. We interpret these results to indicate that all seismic measurements are contaminated by scattering processes that convert body waves to surface waves. Initial work on this topic was published in the following paper:

Al-Shukri, H., G. L. Pavlis, and F. L. Vernon (1995). Site effect observations from broadband arrays, *Bull. Seism. Soc. Amer.*, **85**, 1758-1769.

Additional work was completed a M.S. student of mine (not supported under this project). The citation for his thesis is:

Wilson, D. C. (1997). Near-surface site effects in crystalline bedrock: azimuthal dependence, scale lengths of spectral variation, and changes in spectral character with depth, M.S. Thesis, Indiana University, Bloomington, Indiana, 45 p + CDROM appendix.

I have not enclosed a copy of this paper due to it's length. We are in the process of paring it

down for publication in *Earth Interactions,* which is AGUs new electronic journal. For now the best source for this document is the world-wide web. Text is at http://seismo.geology.indiana.edu/~dcwilson/thesis.html, and a site with links to all the figures (including MPEG movies utilizing a new type of scientific visualization technique we developed) can be found at: http://zelzal.geology.indiana.edu/~dcwilson/rsrch.html.

Scientific Visualization. We have done frontier work in applying scientific visualization techniques to understand data collected by seismic arrays. In addition to Wilson's work (see MPEG movies available by accessing http://zelzal.geology.indiana.edu/~dcwilson/rsrch.html.) another student, Dimitri Repin, developed a related suite of visualization tools for his Ph.D. dissertation. The best representation of this material is his web page at: http://seismo.geology.indiana.edu/hyplan/drepin/ A paper describing this work is in press. A copy of this paper is attached:

Repin, D. And G. L. Pavlis (in press).
Computers in Geosciences.

This paper describes details of new methods we developed to visualize three-component array particle motions, and phase velocity variations within a given seismogram.

Multiwavelet transform results. A parallel award to this grant was obtained from the AASERT program. (For reference. this is AFOSR Grant No. F49620-95-1-0366) This grant supported Ph.D. dissertation research by Lorie Bear. Ms. Bear completed here Ph.D. dissertation defense in December of 1997. The following is the title of her dissertation:

Bear, Lorie (1997). The use of multiwavelets for seismic array data processing, Ph.D. dissertation, Indiana University, Bloomington, Indiana.

Her dissertation is actually three papers: one is published, one submitted, and the third will be submitted shortly. The published and submitted papers are enclosed with this report. The third paper will be appended to the final report for the AASERT grant. The relevant citations are:

Bear, L. K. and G. L. Pavlis (submitted). Multichannel estimation of time residuals from seismic data, *J. Geophys. Res.*

Bear, L.K. and G.L. Pavlis (1997) Estimation of slowness vectors and their uncertainties using multiwavelet seismic array processing, *Bull. Seism. Soc. Amer.*, **87**, 755-769.

Major results. The work we have done on high frequency wavefields will, we believe, have a profound long-term effect on our understanding of high-frequency seismology. Some key elements we believe our work has demonstrated are the following:

- The near-surface waveguide profoundly alters seismic signals at any frequency were the travel time through the weathered layer is comparable to the period of the wave.
- Differential weathering and possibly other effects can cause the near surface to be a profoundly anisotropic media. Measurements by Bear found instances of particle motions as much as 30 degrees away from the theoretical direction based on the

standard isotropic model.

- The weathered layer in chemically weathered crystalline rock is an incredibly heterogeneous media that strongly scatters seismic waves at any frequency were the travel time through the weathered layer is comparable to the period of the wave.

The best summary of these observations at present is contained in the last report we submitted for the research symposium in 1996:

Pavlis, G.L., D. Repin, S. Radzevicius, and F. Vernon (1996). Near-Surface effects on high-frequency seismic waves: Observations from dense, three-component seismic arrays, *Proceedings of the 18th annual seismic research symposium on monitoring a comprehensive test ban treaty, Report PL-TR-96-2153*, 251-260.

A copy of this report is also attached.

Personnel Supported

1. The P.I. was supported for one month of summer salary each year of the project, and has given roughly 30% of his academic year time to this project.

2. The project has supported one graduate student, Dimitri Repin, for the bulk of his Ph.D. work. Repin currently is working for Amoco and has not yet completed his degree. I anticipate, however, that he will defend his dissertation within the next three months as I have received a rough draft of the document.

3. Hanan Mahdi, a post-doctoral research associate, was supported under this project for 6 months each year (5 months plus November 1995) for three years. She is the major person responsible for results done under Task 1.

Publications

Papers and reports: (see above)

Published Abstracts:

Bear, L. K. and G. L. Pavlis (1997). High-resolution multiwavelet seismic array processing, *EOS Trans. Amer. Geophys. Union,* **78**, S217.

Bear, L. K. and G. L. Pavlis (1996). Multiwavelet estimation of bearing and slowness uncertainty from broadband seismic arrays, *Seism. Res. Letters*, **67**, 32.

Mahdi, H. H. and G. L. Pavlis (1996). Lateral velocity variations in the crust and upper mantle beneath the Tien Shan from Surface waves: implications for tectonic and dynamic processes, *Seism. Res. Letters*, **67**, 45.

Repin, D. G. and G. L. Pavlis (1996). Three-dimensional visualization of seismic array data, *Seism. Res. Letters*, **67**, 52.

Mahdi, H. H. And G. L. Pavlis (1995). Crustal and uppermost mantle structure beneath eastern Tien Shan from broadband surface wave data, *Geol. Soc. Amer. Abst. With Programs-1995*, A-193.

Pavlis, G. L. (1995). When do triaxial geophone groups reduce noise?, *Trans. Amer. Geophys. Union,* **76**, F367.

Mahdi, H. H., and G. L. Pavlis (1995). Spatial stability of Rayleigh wave amplitudes and path dependent stacking capabilities of the Kyrghystan broadband network, *Trans. Amer. Geophys. Union,* **76**, F380.

Repin, D. and G. L. Pavlis (1995). Triggered events or scattered arrivals? Interactive array analysis and visualization, *Trans. Amer. Geophys. Union,* **76**, F408.

Pavlis, G. L., and F. L. Vernon (1995). High-frequency resonance observations at hard rock sites, *EOS Trans. Amer. Geophys. Union,* **76**, S202-S203.

Bear, L. and G. L. Pavlis (1995). Variable bandwidth analysis of broadband seismic array data, *EOS Trans. Amer. Geophys. Union,* **76**, S203.

G.L. Pavlis and F.L. Vernon (1994). High Frequency site effects: observational results from small aperture arrays, *EOS Trans. Amer. Geophys. Union*, 75, p. 69.